Feasibility of Technologies to Produce Coal-Based Fuels with Equal or Lower Greenhouse Gas Emissions than Petroleum Fuels

A Study by the United States Secretary of Defense
Requested in Senate Report 113–44, to accompany S. 1197,
the National Defense Authorization Act of Fiscal Year 2014

Prepared by

Office of the Assistant Secretary of Defense for
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Acquisition, Technology, and Logistics

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14. ABSTRACT
This report examines the feasibility of potential technologies that could enable coal-based fuels to meet the requirements of the DoD consistent with section 526 of the Energy Independence and Security Act (EISA) of 2007 (Public Law 110-140). The report also discusses research on those technologies that are most promising for the reduction of greenhouse gas emissions, capture of carbon, and other approaches that could enable coal-based fuels to be procured under section 526 of the EISA 2007.

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THE UNDER SECRETARY OF DEFENSE
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ACQUISITION, TECHNOLOGY AND LOGISTICS

The Honorable Carl Levin
Chairman
Committee on Armed Services
United States Senate
Washington, DC 20510

DEC 22 2014

Dear Mr. Chairman:

The enclosed report fulfills your committee's request in the Senate Report 113–44, pages 84-85, accompanying S. 1197, the National Defense Authorization Act for Fiscal Year 2014. As requested, the Secretary of Defense, in consultation with the Secretary of Energy, is reporting to the committee on the feasibility of potential technologies that could enable coal-based fuels to meet the requirements of the Department of Defense consistent with section 526 of the Energy Independence and Security Act of 2007 (Public Law 110–140).

Sincerely,

Frank Kendall

Enclosure:
As stated

cc:
The Honorable James M. Inhofe
Ranking Member

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Acronyms and Definitions

Technical Terms

bpd	Barrels per day
BTL	Biomass-to-liquids
CBTL	Coal-and-Biomass-to-Liquids
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalent (metric measure used to compare the emissions from various greenhouse gases based upon their GWP)
CTL	Coal-to-liquids
F-T	Fischer-Tropsch (a type of synthesis to produce hydrocarbons from syngas)
GHG	Greenhouse gas
GTL	Natural gas-to-liquids
GWP	Global warming potential (measure of the total energy that a gas absorbs over a particular period of time—usually 100 years—compared to carbon dioxide)
IGCC	Integrated gasification combined cycle
MMbpd	Million barrels per day
MSW	Municipal solid waste
MTG	Methanol-to-gasoline
SNG	Synthetic natural gas (i.e., mostly methane)

Administrative Terms

AEO	EIA Annual Energy Outlook
AFRL	(DoD) Air Force Research Laboratory
DLA	(DoD) Defense Logistics Agency
DoD	Department of Defense
DOE	Department of Energy
EIA	(DOE) Energy Information Administration
EPA	Environmental Protection Agency
FOA	Funding opportunity announcement
IEO	EIA International Energy Outlook
NETL	(DOE) National Energy Technology Laboratory
OSD	(DoD) Office of the Secretary of Defense
R&D	Research and development
RD&D	Research, development, and demonstration
RDT&E	Research, development, testing and evaluation

Executive Summary

Coal is one of the most abundant energy resources in the United States and worldwide and was used as a fuel in the first generation of steam ships and locomotives. Today, engines for mobility applications almost exclusively use petroleum-based liquid fuels, though coal can be converted into fuels that are virtually identical to those derived from petroleum. Domestic production of coal-to-liquids (CTL) fuels that can substitute for petroleum fuels could offer benefits in terms of trade balance, economic development, and energy security. Technologies for producing CTL fuels were developed and commercialized in the first half of the 20th century, and several new facilities are being planned. Because CTL production processes are inherently more difficult and complex (and thus less energy efficient) than petroleum refining, the commercial viability of CTL fuels depends on coal being significantly cheaper than crude oil on an energy basis. Additionally, current technologies to produce CTL fuels result in greater life-cycle greenhouse gas (GHG) emissions than petroleum fuels.

Section 526 of the Energy Independence and Security Act (EISA) of 2007 (Public Law 110-140) effectively prohibits Federal agencies from entering contracts to explicitly procure alternative fuels with greater life-cycle GHG emissions than conventional petroleum-derived fuels. This report identifies obstacles and provides an overview of technology opportunities to reduce costs and GHG emissions associated with coal-based fuels production, with a focus on liquid fuels that would be subject to EISA section 526. Major opportunities to reduce GHG emissions of CTL fuels fall into three categories: increasing conversion technology efficiency; supplementing coal with feedstocks and energy inputs that have lower life-cycle GHG emissions; and carbon capture, utilization, and storage (CCUS). Without at least one of the latter two measures, coal-based liquid fuels will not meet the requirements of EISA section 526.

In 2013, Congress appropriated $20 million to the Department of Defense (DoD) to advance technology through research and development on technologies that will potentially enable CTL fuels to comply with section 526. DoD then teamed up with Department of Energy (DOE) in order to leverage DOE's technical expertise, capabilities, and complementary agency mission pertaining to alternative fuels. DOE supports research on the production of power, fuels, and chemicals from domestic coal and biomass resources using methods that are less damaging to the environment. DoD, by comparison, is a large fuel customer that evaluates fuels produced through new pathways that may be integrated into commercial-scale supplies of military fuels, but it generally does not develop new production technologies for large-scale commodity fuels.

Prior to posting this $20 million funding opportunity announcement (FOA), DoD and DOE analyzed state-of-the-art CTL technologies available today; ongoing research, development, and demonstration (RD&D) activities; and relevant new RD&D opportunities. This analysis was the basis for the FOA, and it concluded that—with successful RD&D—it is feasible to develop technologies that would enable production of section 526-compliant and cost-competitive CTL jet fuel, consistent with the alternative fuel requirements of DoD. In this FOA, the two agencies are co-funding projects with the aim of overcoming technical challenges associated with producing section 526-compliant and cost-competitive CTL jet fuel, through advancing technologies such as hybrid processes, process intensification, innovative concepts, and demonstrating the feasibility of site-specific CTL facilities in the United States. Periodic reassessment of the status of CTL technology will be performed as RD&D progresses, to identify technical areas where continued funding will have the most beneficial impacts.

I. Introduction

Approximately 19 million barrels (800 million gallons) of petroleum products are supplied each day to U.S. consumers [1]. The majority of these products are liquid fuels for transportation, as presented in Figure 1, though other products such as liquefied petroleum gas (LPG) and petrochemical feedstocks are not insignificant. In 2013, 92 percent of U.S. transportation fuel was sourced from petroleum, three percent from natural gas (mostly used in operating pipeline compressors), and a negligible amount from coal; just under five percent was produced from biomass—mostly in the form of corn-derived ethanol that is blended into gasoline, and biodiesel to a much smaller extent [1]. With the limited exception of experimental and demonstration use of alternative jet fuels, all of the jet fuel currently consumed in the United States is derived from petroleum.

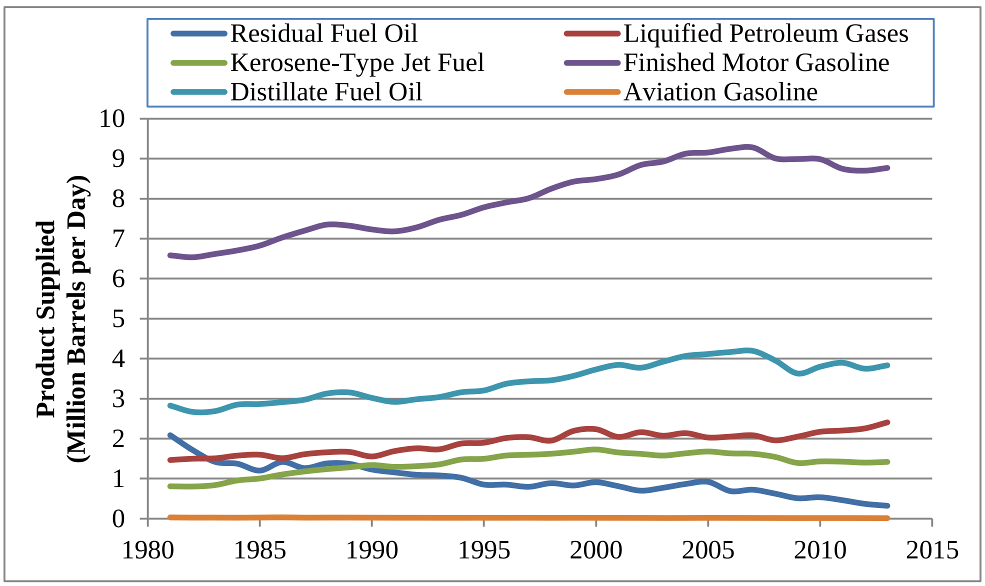

Figure 1. Supply of major types of petroleum-based transportation fuel products in the United States from 1981 to 2013 [data obtained from US DOE [2]][1]

Coal is less expensive and more abundant than many other feedstocks being targeted for alternative fuel production, but coal-based alternative fuels are not produced at commercial scale in the United States. Despite the low cost of coal as a feedstock, financial challenges associated with constructing and operating coal-to-liquids (CTL) facilities have prevented the development of a successful CTL industry in the United States. An additional challenge that may limit demand for CTL fuels, even if produced in a manner that is cost-competitive with conventional petroleum fuels, pertains to the quantity of greenhouse gases (GHG) emitted during their production. As CTL production methods exhibit a life-cycle GHG emissions profile approximately twice that of conventional petroleum fuels, section 526 of the Energy

[1] Total U.S. product supply is approximately 19 million barrels (800 million gallons) per day, or 7 billion barrels (300 billion gallons) per year.

Independence and Security Act (EISA) of 2007[2] effectively prohibits Federal agencies that purchase fuel (DoD being the largest) from contracting explicitly for the procurement of CTL fuels that have been produced without sufficiently curtailing life-cycle GHG emissions. This report identifies obstacles and potential solutions to produce CTL fuels that have a GHG emissions intensity that is equal to or lower than conventional petroleum fuels, in response to a request from the Senate Report 113–44, pages 84-85, accompanying S. 1197, the National Defense Authorization Act (NDAA) for Fiscal Year 2014, which reads:

> Additionally, the committee directs the Secretary of Defense, in consultation with the Secretary of Energy, to report to the committee on the feasibility of potential technologies that could enable coal-based fuels to meet the requirements of the DoD consistent with section 526 of the Energy Independence and Security Act (EISA) of 2007 (Public Law 110–140). The report shall also include a proposal for joint research on those technologies that are most promising for the capture of carbon, reduction of greenhouse gas emissions, and other approaches that could enable coal-based fuels to be procured under section 526 of the EISA 2007.

II. Background

1. Overview of Alternative Fuel Production Processes

Chemical transformation processes with varying energy- and cost-intensities are required to convert non-petroleum feedstocks into fuel products that can be blended with petroleum-based fuels. For example, vegetable oils and animal fats can be converted to liquid fuels through chemical conversion and hydroprocessing (similar to the conversion of crude oil into petroleum products) with comparable process intensity to petroleum refining. The approaches for converting coal and other solid feedstocks into liquid fuels are typically categorized as 'direct' liquefaction and 'indirect' liquefaction, as presented in Figure 2; both synthesis pathways have a well-established history, but demand more energy-intensive processes than conventional oil refining.

Direct liquefaction of coal entails reacting coal with hydrogen at high pressure and temperature to produce raw liquids, which must subsequently be refined into final fuel products. This technology was initially developed by Frederick Bergius in Germany just over 100 years ago [3], and has been intermittently refined over the years. A direct liquefaction process is currently

[2] Energy Independence and Security Act of 2007, Pub. L. No. 110–140, § 526, 121 Stat. 1492, 1663 (2007), codified at 42 U.S.C. § 17142, states that "No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility-related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources." (*EISA 2007 §526, Public Law 110–140)*

utilized commercially by the Shenhua Group at the Shenhua Direct Coal Liquefaction Plant in Erdos, Inner Mongolia.

Indirect conversion of coal entails a gasification process that transforms the material into synthesis gas (syngas)—primarily a mixture of hydrogen, carbon monoxide, and some carbon dioxide—which in turn is a feedstock for liquid fuels synthesis routes such as methanol synthesis or the Fischer-Tropsch (F-T) process. Methanol can be used as a liquid fuel or fuel blendstock on its own, or as a feedstock for gasoline production through conversion pathways such as ExxonMobil's methanol-to-gasoline (MTG) process, which was developed in the 1970s [4] and commercialized in New Zealand in the 1980s. The F-T process, initially developed in the 1920s by Franz Fischer and Hans Tropsch [5], produces hydrocarbons that can be refined into liquid transportation fuels or other products. F-T technology was successfully utilized in Germany during World War II and the government of South Africa during apartheid era sanctions; the same approach is still used today on a large scale by Sasol in South Africa and in multiple new projects in China.

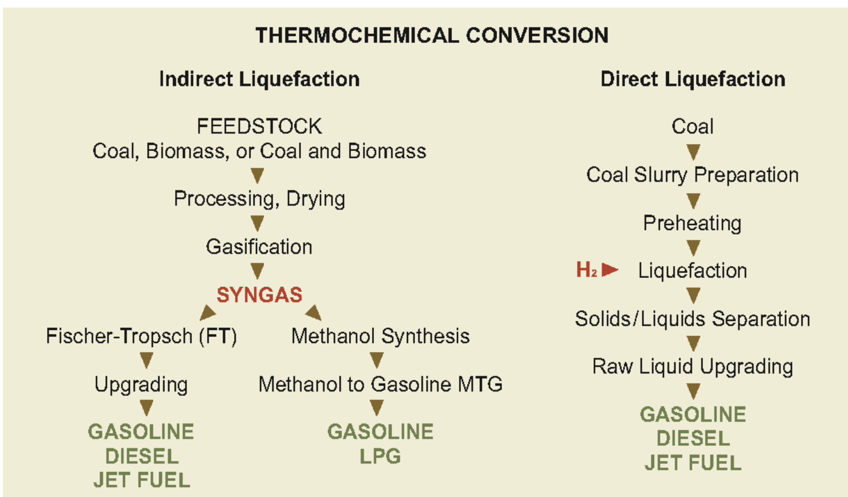

Figure 2. Direct and indirect feedstock-to-fuel thermochemical conversion processes [reproduced from [6]]

2. The DoD and Alternative Fuels

The Department of Defense (DoD) is one of the largest institutional fuel consumers in the world, and has historically supported innovations for evaluating and utilizing new fuels and propulsion systems for mobility applications. Although nuclear, solid, gaseous, and specialty fuels are used for ship propulsion, missile propellants, and other unique applications, the military predominantly consumes the same types of liquid fuels as the commercial transportation sector. The vast majority of DoD's fuel demand is for jet fuels, which are predominantly composed of hydrocarbons nine to 15 carbons long (abbreviated as C9-C15), diesel fuels (C8-C25), and to a lesser extent gasoline fuels (C4-C12). For most of DoD's purposes, the term 'alternative fuels' refers to liquid fuels that are predominantly derived from non-petroleum resources, which could include fossil fuels such as coal and natural gas, or renewable resources such as biomass and

wastewater sludge. For operational purposes, DoD is primarily interested in evaluating and procuring alternative fuels that are considered "drop-in" (i.e., interchangeable with existing petroleum hydrocarbon fuels and compatible with existing infrastructure and equipment), are competitive with petroleum-based fuels in meeting DoD's performance and cost requirements, and comply or are expected to comply with section 526 of EISA 2007 [7]. In recent years, several reports to Congress have addressed DoD's efforts to reduce petroleum fuel consumption through the use of alternative fuels [8,9,10,11].

Whereas DOE is "committed to supporting research focused on making use of the nation's coal and biomass resources for affordable power generation, fuels, and chemicals using methods that are less damaging to the environment" [12], DoD's primary role in supporting alternative fuels development consists of certifying military platforms to use new fuels when new production pathways are likely to be commercialized in the United States or abroad. In fact, DoD has already qualified fuels that contain up to 50 percent alternative fuel produced via the indirect F-T process for use in most operational platforms that use JP-8, JP-5, and F-76 fuels (which are traditionally petroleum-based). Additional pathways for producing liquid fuels from coal or other solid feedstocks, such as direct liquefaction, have not yet been approved. Due to the wide range of potential processing conditions that may be used to produce fuels via direct liquefaction and potentially other new pathways, approval may be limited to specific types of feedstocks (e.g., coal of a certain quality) and/or specific ranges in process conditions (e.g., pressure, temperature).

To our knowledge, the only CTL fuels that have been purchased for operational purposes by DoD were purchased in South Africa. The quantity of CTL fuel purchased cannot be confirmed; however, as operational fuel procurement contracts managed by the Defense Logistics Agency Energy (DLA Energy) only require suppliers to confirm that the fuels meet quality specifications, but typically do not require information about the type or origin of feedstocks used in producing the provided fuels. Because bulk fuel supply contracts do not specify or stipulate the type of feedstock to be used, DoD has not "enter[ed] into a contract for procurement of an alternative or synthetic fuel" for purposes of section 526. Consequently, DLA Energy has not yet had occasion to evaluate fuels for compliance with EISA section 526.

3. Potential and Projections for Coal-based Liquid Fuel Production

A large alternative fuels industry that capitalizes on resources that are abundant in the United States may benefit the nation in terms of trade balance, economic development, and energy security. As the United States contains approximately 27 percent of global coal reserves [13]—a greater resource than most other domestic alternative fuel feedstocks—Executive and congressional support for CTL R&D (including the passage of the Synthetic Fuels Act) initially grew in the 1940s, though interest and funding has fluctuated over time [14]. Numerous studies have reviewed the long history of CTL technology development and policies within the United States [14,15,16,17]. Over the last seven decades, significant progress has been made on producing coal-derived transportation fuels, synthetic natural gas (SNG), and chemicals.

From 2010 through 2040, the United States is anticipated to increase coal production from approximately 1.0 to nearly 1.1 billion tonnes (1.1 to 1.2 billion short tons) per year, as global production increases from approximately 7.2 to 10.5 billion tonnes (8.0 to 11.5 billion short tons) per year by 2040 [13]. Domestic consumption of coal is anticipated to remain around 900 million tonnes per year through 2040, and coal is expected to be predominantly used for power production [1]. For reference, total demand for liquid fuels in the United States is expected to remain just under 20 million barrels per day (MMbpd) through 2040, while global demand is anticipated to increase from approximately 90 MMbpd in 2013 to 120 MMbpd in 2040, according to the reference case in DOE's 2013 International Energy Outlook [13].

A wide range of yield values for the conversion of coal into liquid fuels have been reported (or implied) in previous literature—from 1.0 to 3.0 barrels of CTL fuel per tonne of coal—with experience from Sasol indicating that a range of 1.0-1.5 barrels per tonne is realistic with existing technologies [18]. Figure 3 illustrates the additional quantity of coal that would be needed to support a hypothetical growing U.S. CTL industry capable of producing 5 MMbpd of liquid fuels by 2040, assuming a yield of two barrels of liquid fuel per tonne of coal (corresponding to a conversion energy efficiency of approximately 43 percent, ignoring electricity and other potential outputs). In this example, approximately 210,000 bpd in new CTL production capacity would come online every year after 2016. By 2040, demand for coal in the United States would be more than twice the projected coal demand in DOE's Annual Energy Outlook (AEO) reference case scenario, and CTL fuels would meet approximately 27 percent of domestic demand for liquid fuel.

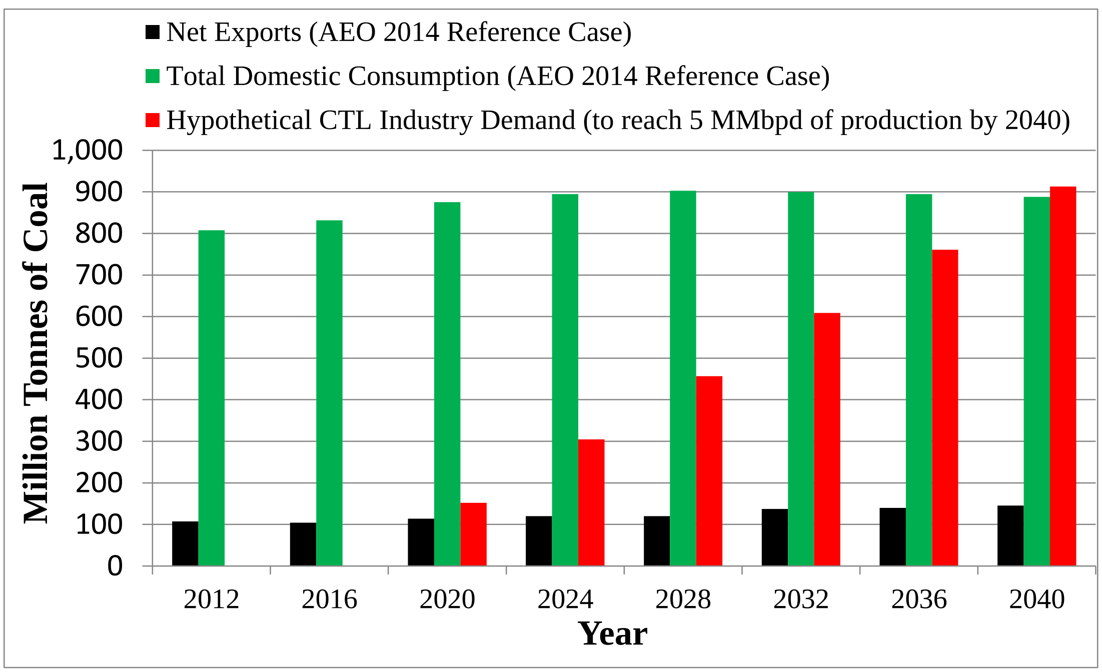

Figure 3. Quantity of coal projected to be consumed within and exported (net) from the United States [data obtained from DOE [1]], and hypothetical demand for coal to support a growing CTL industry capable of producing 5 MMbpd of liquid fuels by 2040 (assuming a yield of 2.0 barrels per tonne of coal).

Although a rapid and significant scale-up in CTL production capacity may be technically achievable, past and projected CTL projects in the United States and abroad remain minor in scale compared to the petroleum refining industry. A number of CTL projects have been proposed in the United States in recent decades—most of them at times of combined high oil and natural gas prices. No commercial projects have been completed to date, and the increasing availability of domestic petroleum and low-cost natural gas pose a challenge for many alternative fuels to be economically competitive. In fact, DOE's 2014 AEO does not project any domestic CTL production by 2040, except under the high crude oil price scenario (i.e., exceeding $150/barrel after 2020)—although production in this case will not even exceed 75 million barrels per year (0.2 MMbpd). For comparison, approximately 400 million barrels per year (1.1 MMbpd) of renewable fuels are anticipated to be in production by 2040 in the reference and high oil price scenarios—which is still only six percent of anticipated total product supplied [1].

Commercially established CTL fuels production is primarily located outside the United States, specifically in South Africa (Sasol's extensive CTL complexes at Sasolburg and Secunda) and China (Shenhua's direct coal liquefaction and indirect coal liquefaction in Inner Mongolia). By 2040, production of CTL globally is anticipated to be centered in China (over 60 percent), South Africa (over 25 percent), and India (7 percent), resulting in total production of 400-1,000 million barrels per year (i.e., between 1.0 and 2.6 MMbpd, depending on oil price assumptions), albeit making up less than 2.5 percent of global liquid fuel supply [13]. Previous international RD&D efforts have focused on improving efficiency, lowering capital and operating costs, minimizing water use and wastewater discharges, etc., but reducing GHG emissions has not yet been a driver of CTL RD&D in these cases. Nonetheless, as extensive future RD&D in CTL production will take place overseas, and reduction of GHG emissions becomes a global priority, RD&D associated with international ventures should be leveraged.

4. Domestic Carbon Capture RD&D Efforts

Carbon capture, utilization, and storage (CCUS) is a set of technologies that reduces CO_2 emissions to the atmosphere by capturing CO_2 from the source (e.g., power plants and industrial facilities), and then transporting it to a location for utilization in industrial processes or long-term geologic storage (also referred to as sequestration). Carbon capture from coal gasification-derived syngas (which is likely to play a prominent role in GHG reduction for CTL processes) is currently practiced at the Great Plains Synfuels plant and will be undertaken at the nearly completed Kemper County integrated gasification combined cycle (IGCC) project in Mississippi. The latter plant will capture and use 65 percent of the CO_2 it produces through enhanced oil recovery. DOE continues to fund carbon capture and storage (CCS) technology R&D to improve efficiency and costs of existing and nascent advanced CCS technologies.

III. Promising Areas for Coal-to-Fuel Technology R&D

Existing CTL conversion technologies that are being used commercially produce fuels with approximately twice the life-cycle GHG emissions of conventional petroleum (i.e., approximately 200 versus 100 g CO_2eq per MJ of fuel energy). CTL fuels are differentiated from petroleum fuels due to their higher "well (or mine)-to-tank" emissions—i.e., emissions that occur prior to use (combustion) in vehicles—as the combustion of standard liquid fuels in common engines results in similar direct (tailpipe) CO_2 emissions per unit of fuel energy (i.e., 70-78 g CO_2/MJ), whether the fuel is produced from coal, petroleum, or biomass; additionally, CO_2 has the same effect in the atmosphere regardless of its feedstock of origin.

The primary difference between CTL fuels and petroleum fuels is attributed to emissions associated with fuel production, as conversion of coal into liquid fuels consumes much more energy (resulting in CO_2 emissions) than refining crude oil to petroleum. As a result, CTL fuels that are currently available would not meet EISA section 526 requirements. Appendix A presents a brief overview of life-cycle assessment (LCA) framework, a range of CTL, biomass-to-liquids (BTL), and coal-and-biomass-to-liquids (CBTL) emission factors reported in relevant literature, the economic impact of emissions reduction strategies, and methodological considerations that could increase or decrease the GHG emissions attributed to CTL fuels (e.g., allocation of emissions to co-products and infrastructure, differentiating CTL fuels from petroleum fuels).

The potential exists to substantially lower life-cycle GHG emissions of CTL through advancing technology. A team of experts from DOE and DoD reviewed a range of process modifications, technological improvements, and life-cycle optimization options that would lower the energy and GHG intensity of CTL fuel production. Current options for reducing the GHG footprint of coal-based fuels to an acceptable level to meet EISA section 526 include: (1) improving conversion technology efficiency, (2) supplementing coal feed with feedstocks that have lower life-cycle GHG emissions (e.g., natural gas and biomass), and (3) improving and implementing CCUS. These options are not necessarily listed in order of potential cost-effectiveness for CTL producers to meet section 526 criteria or in order of cost-effectiveness to minimize economy-wide GHG emissions. Non-technical options for reducing emissions (e.g., purchase of carbon offset credits) are outside the scope of this report.

1. Conversion Technology Improvement

Improving the efficiency with which feedstocks are converted and refined to fuels and other products will correspondingly reduce the overall GHG footprint (a.k.a. "carbon footprint") of a CTL process—partially narrowing the gap in well (or mine)-to-tank GHG emissions between CTL fuels and petroleum fuels. Of significant importance to the GHG emissions from fuel production is the fraction of input energy required to drive the conversion processes. While most U.S. refineries conserve close to 90 percent of the input energy content when refining crude oil to fuels [19], the production of synthetic fuels from coal is significantly less efficient.

It has previously been suggested that the theoretical maximum thermal efficiency of producing synthetic fuels through indirect processes (i.e., gasification and F-T synthesis) from coal is 60 percent [20,21], whereas the indirect synthesis of hydrocarbon fuels or methanol from natural gas could reach 75 percent to 8 percent thermal efficiency [20,21,22]. Unfortunately, operating thermal efficiencies rarely exceed 80 percent of theoretical efficiency in practice—e.g., 63 percent for Shell's gas-to-liquids (GTL) hydrocarbon fuel pathways [21,23,24], 72 percent (versus 84 percent) for natural gas to methanol and 58 percent (versus 75 percent) for methanol-to-gasoline [22], and only 40 percent for CTL facilities [15,25]. Although liquid fuels can be produced from coal via direct liquefaction with overall thermal efficiencies of approximately 70 percent, such fuels require additional energy-consuming processing in order to resemble petroleum fuel products [18].

Recently published CTL, BTL, and CBTL production scenarios that incorporate the production of both hydrocarbons and electricity suggest that no more than 55 percent of energy inputs will end up in the form of marketable energy outputs [25,26,27], and the fraction of coal directed towards producing electricity (or other co-products) will affect the breakeven price and GHG emissions allocated to liquid fuel outputs. In fact, the portion of coal's carbon anticipated to leave an indirect CTL facility in the form of liquid hydrocarbon fuel is typically just over 30 percent [28], assuming coal is the predominant energy input. As a result, the majority of coal's carbon will leave as CO_2, and there are very few ways of minimizing the amount of that CO_2 that escapes to the atmosphere—CCUS being an example.

Advances in unit operations of coal conversion and fuels synthesis processes have the potential to make a cumulative impact on improving energy efficiency, reducing process costs, and reducing life-cycle GHG emissions. Appendix B presents a list of unit operations and process elements where technological improvements are possible—many of which are expected to garner attention in future R&D work. In general, these fall into the main process areas listed below.

- Feed Systems (e.g., feedstock preparation, handling, and injection)
- Air Separations (alternative, efficient technologies for oxygen generation)
- Gasification Systems (e.g., advanced coal and coal/biomass gasification, gasification of residual solids from direct coal liquefaction technologies, chemical looping)
- Synthesis Gas Cleanup (e.g., technologies that improve thermal efficiency and lower cost while achieving requirements of downstream conversion processes)
- Separations (e.g., hydrogen separation/recovery, CO_2 separation/capture, solids/liquids separation, solvent recovery/recycle)
- Conversion Processes (e.g., synthesis gas conversion, coal liquefaction/hydrogenation, product upgrading, chemical looping, novel catalysts and reactor design, olefin oligomerization)

2. Feedstock and Energy Input Supplementation

Coal inherently contains more carbon per unit energy (e.g., BTU or MJ) than petroleum,[3] meaning that in converting coal to standard hydrocarbon liquid fuels with characteristic carbon to hydrogen ratios, CO_2 emissions will be higher for coal-based fuels than for petroleum fuels—even if the coal-to-fuel conversion process could be accomplished with the same energy efficiency as the petroleum fuel refining processes. As a result, a potential solution is to supplement CTL production with feedstocks that reduce the average life-cycle GHG intensity of the inputs and, hence, the finished fuel. For the purposes of this report, fuel produced from multiple feedstocks may still be considered a "coal-based fuel" if the majority of (but not necessarily all) input energy comes from coal (consistent with solicitation DE-FOA-0000981). Reduction in average life-cycle GHG emissions through feedstock and energy input supplementation may be accomplished by replacing some of the coal feed with the following:

1. **Biogenic Carbon**: Coal may be blended with carbon-containing biomass feedstocks that would otherwise not have grown on a given land area (e.g., purpose-grown energy grasses and trees with minimal adverse land use change impacts) and/or would otherwise biodegrade (e.g., agricultural and forestry residues). Although some amount of fossil fuel is typically required to plant, harvest, handle, and transport all feedstocks, the GHG emissions from these activities (per unit of feedstock energy) are typically much less than the fossil carbon intensity of coal and other fossil fuels. For example, up to the point of transporting biomass bales to a conversion facility, the life-cycle GHG emission factor for purpose-grown Miscanthus grass has been estimated at just under 8 g CO_2eq/MJ if assuming negligible net impacts on soil carbon and global land use change [31], with much lower (even negative) emissions calculated if soil carbon stocks increase under a biomass cropping system and/or if electricity output from the conversion facility displaces coal-fired power [32]. Alternatively, if production of biomass requires significant carbon inputs for fertilizer, pesticides, etc. (as is commonly reported for soy- and corn-based biofuels), and/or if biofuel production results in land use change causing deforestation (as has been reported for oil palm biofuels), the GHG emissions factor for biomass feedstocks may even exceed that of petroleum. Additionally, incorporating biomass into a CTL process would entail additional costs and emissions associated with handling and processing of biomass at the facility.
2. **Waste Carbon**: Coal may be blended with carbon-containing waste feedstocks (e.g., municipal solid waste (MSW), wastewater sludge). Waste streams may contain both biogenic carbon and fossil carbon. The organic portion of wastes (e.g., paper, food waste, sludge) is typically assumed to biodegrade to CO_2 (and potentially some

[3] This distinction pertains to the chemical properties of the fuel itself, and should not be confused with 'fuel carbon intensity' (FCI) which has been used to describe the life-cycle GHG emission factors of various fuels [29]. Although biomass and biofuels often have a carbon-to-energy ratio that is similar to their fossil fuel counterparts, these fuels are often reported to have a low life-cycle GHG intensity (or FCI) because renewable biogenic carbon would decay and release CO_2 (and not sequester carbon) if not utilized for bioenergy applications [30].

methane—a more potent greenhouse gas—if waste is held in anaerobic conditions) if not used for fuel production, as is the case for agricultural and forestry residues. Within the United States, the portion of waste feedstocks that are not expected to biodegrade (e.g., non-recyclable plastics containing fossil carbon, pressure-treated wood containing biogenic carbon) would typically sequester carbon in landfills if not used for fuel production. Since it is already collected and transported to a facility, non-biodegradable waste feedstocks could have a lower GHG emissions intensity than some fossil fuels by avoiding emissions associated with extracting and transporting fossil fuels to a facility, and avoiding emissions associated with maintaining waste within a landfill.

3. **"Fossil Hydrogen" from Natural Gas:** Supplementing coal with fossil fuels that have a greater "fossil hydrogen" to "fossil carbon" ratio could reduce the average GHG emissions intensity of inputs, and thereby reduce the GHG emissions attributed to outputs. As naturally occurring pure hydrogen (H_2) resources are extremely rare, natural gas is the fossil fuel with the greatest likelihood of enabling the average life-cycle carbon emissions of a fuel derived partially from coal to be less than petroleum fuels. With a combustion emissions factor of approximately 50 g CO_2 per MJ of fuel,[4] natural gas contains over 30 percent more energy per unit of fuel carbon than petroleum fuels and over 70 percent more energy than coal (which have emission factors of approximately 70 g CO_2/MJ and over 88 g CO_2/MJ, respectively) [33]. Nonetheless, without employing CCUS, production of GTL fuels (without any coal) results in greater GHG emissions than conventional petroleum fuels, given the low thermal efficiency of current conversion technologies (i.e., gasification and F-T synthesis) as discussed in the previous section.
4. **Low-GHG Process Energy or Hydrogen**: Whereas a standard CTL facility configuration would entail using coal's energy to supply all of the process energy needs, a reduction in the average life-cycle GHG emissions intensity of CTL products may be accomplished by supplementing a facility's process energy requirements with low-GHG energy sources. In addition to providing electricity to a CTL facility, renewable or nuclear energy could be used to produce hydrogen inputs for CTL production, which would reduce the amount of coal energy consumed (and CO_2 emitted) in producing hydrogen. Incorporating heat, electricity, and/or hydrogen from a nuclear reactor into a CTL process may reduce CO_2 emissions by more than 75 percent [34,35].

3. Carbon Capture, Utilization, and Storage (CCUS)

Another opportunity to reduce the life-cycle GHG emissions from CTL production is to employ CCUS processes that prevent facility CO_2 emissions from reaching the atmosphere. For the purposes of this report, the incorporation of CCUS processes at a CTL facility would reduce the "lifecycle greenhouse gas emissions associated with the production and combustion of the fuel," which are regulated by EISA section 526. The more common acronym, CCS, does not include

[4] Combustion emissions are a major component of life-cycle emissions; however, a life-cycle emissions factor would also incorporate emissions associated with exploration, production, distribution, and other activities, as discussed in Appendix A

potentially valuable CO_2 utilization opportunities; however, under some circumstances, removed CO_2 could be compressed and gainfully utilized for industrial purposes such as enhanced oil recovery. Under the economically conservative assumption that utilization is infeasible, CO_2 is assumed to be injected into geologic reservoirs for long-term storage.

Capture of CO_2 emissions from F-T CTL facilities would typically involve relatively efficient pre-combustion CO_2 removal from partially shifted (reacted) syngas—the purpose being to increase the hydrogen content of the syngas. In the case of direct CTL, if fossil fuels are used to generate the hydrogen needed for fuel upgrading, there will be a need for CO_2 removal to produce this hydrogen. The addition of a CCS process to a CTL facility (which has a relatively pure stream of CO_2) has been suggested to cost approximately \$5/t-CO_2 (while adding four percent to plant capital costs)—adding only \$0.07/gallon to the required selling price (RSP) of diesel fuel, and resulting in life-cycle GHG emissions 5-12 percent less than petroleum fuels [36]. Recent studies have estimated that adding CCS to a CTL facility would entail a slightly higher cost of \$12/t-CO_2 to \$35/t [26]. For comparison, capturing CO_2 from coal-fired power plants requires the removal of (relatively low concentration) CO_2 from exhaust that primarily consists of nitrogen (due to the composition of input ambient air), and is typically projected to cost close to \$60/ton.

Several reports have identified that the cost of CCS has risen over the last decade, largely due to inflation in the construction industry, increasing energy prices, and fuel costs [37]. In addition to cost concerns, CCS challenges include demonstrating long-term stability, regulation, social acceptance, investment and operation costs, and lack of policies for emission reduction via CCS [38]. In a survey of experts, in addition to technological costs and barriers, four main barriers to CCS commercialization were identified: (1) cost and cost recovery, (2) lack of a price signal or financial incentive, (3) long-term liability risks, and (4) lack of a comprehensive regulatory regime [39]. To put the long-term risk associated with nonpermanent sequestration in perspective, it has been estimated that leakage rates of one percent per year would render CCS ineffective for climate change, though 0.1 percent would be acceptable [40].

IV. DOE Program Efforts in Supporting Technologies

DOE has research and development programs in place which address several technology areas relevant to CTL. In particular, the National Energy Technology Laboratory's (NETL) Strategic Center for Coal's (SCC) Clean Coal Research Program supports RD&D activities aimed at improving the performance and reducing the cost of today's coal-based systems, with an emphasis on CCS. The SCC is supporting the investigation of a range of advances in combustion, gasification, turbines, fuels, and fuel cell technology for processes of any type that consume coal, including power production and fuels synthesis processes. Program areas directly related to CTL are discussed below.

1. Gasification Systems

Gasification is the core technology for syngas production and indirect coal conversion, and represents the largest single capital cost element of a process plant; therefore it is a focus of efforts to improve process efficiency and reduce costs. DOE has significant program efforts in this area, supporting R&D to advance technologies in:

- Gasifier feeding (e.g., development of high-pressure solids pumps for feeding dry coal to gasifiers and other innovative coal feeding technologies);
- Air separation (development of high-efficiency, low cost alternatives to conventional cryogenic oxygen separation);
- Gasifier optimization (e.g., development of improved gasifier refractory, gasifier sensors and process controls, technologies to reduce gasifier syngas cooler fouling and increase gasifier efficiency, and development of novel gasification technologies), and
- Syngas processing (e.g., development of high-efficiency processes that operate at moderate to high temperatures and provide multi-contaminant control to meet the highest environmental standards in syngas cleanup, and efficient, low-cost product gas separations of hydrogen and carbon dioxide).

More information including a list of on-going projects within the Gasification Program can be found at:

http://www.netl.doe.gov/research/coal/energy-systems/gasification

2. Coal & Coal/Biomass to Liquids (C&CBTL)

DOE's Coal and Coal-Biomass to Liquids program effort is focused on technologies to foster the commercial adoption of coal and coal-biomass gasification and the production of affordable liquid fuels and hydrogen with excellent environmental performance. A focus of the program is the production of liquid hydrocarbon fuels from coal and/or coal-biomass mixtures. Incorporating biomass utilization in CTL reduces the overall average life-cycle GHG emissions of liquid fuels produced, with relevancy to EISA section 526 requirements. Specific program activities include support of research for handling and processing of coal-biomass mixtures,

ensuring those mixtures are compatible with feed delivery systems, identifying potential impacts on downstream components, and gasifier optimization.

More information including a list of on-going projects within the C&CBTL Program can be found at:

http://www.netl.doe.gov/research/coal/energy-systems/fuels/coal-and-biomass-to-liquids

3. Carbon Capture and Storage (CCS)

DOE's R&D program in this area focuses on innovative sorbent, solvent, and membrane-based carbon capture technologies in both pre-combustion and post-combustion process scenarios, which show promise for significant performance and cost advantages over currently available carbon capture technologies.

More information including a list of on-going projects within the Carbon Capture and Carbon Storage Programs can be found at the following two websites:

http://www.netl.doe.gov/research/coal/carbon-capture
http://www.netl.doe.gov/research/coal/carbon-storage/research-and-development

V. CTL Jet Fuel Solicitation—Technology Advancement Target Areas

In 2013, DOE's NETL, on behalf of DoD (Air Force), issued a funding opportunity announcement (FOA) seeking applications for coal-based research and development projects on advanced concepts and/or unit operations to reduce GHG emissions from the production of CTL fuels—particularly focused on the production of jet fuel. Projects awarded under the solicitation (DE-FOA-0000981) will be funded by $20 million that was appropriated to the U.S. Air Force under Public Law 113–6, but was not requested in the FY 2013 President's Budget Request.

In developing the solicitation, DOE surveyed recent and ongoing R&D in relevant technology areas, including those listed in previous sections—coal gasification, coal and biomass conversion to liquid fuels, and carbon capture and reduction of greenhouse gas emissions. DOE also assessed all technology development areas requiring advancement to support cost-competitive and lower-emissions CTL processes. Comparing these results enabled identification of outstanding key technology areas requiring advancement in order to support these goals. RD&D areas of interest targeted by this solicitation (explained in detail in Appendix C) include hybrid processes, process intensification, innovative concepts, and demonstrating the feasibility of site-specific CTL facilities in the United States. The specific technology areas identified in the solicitation include the following:

1. Catalysts (greater selectivity, increased production, durability, etc.)
2. Process efficiency (process intensification, heat exchange/heat management, etc.)

3. Multiple or blended feedstocks (biomass, natural gas, etc.)

1. Catalysts

Catalysts for F-T synthesis of fuels from syngas, catalysts for direct coal liquefaction, catalysts utilized in catalytic gasification, etc., may be improved or replaced by innovative new catalysts for more favorable product selectivity, increased capacity for production, lower cost, durability in operation (i.e., having lower attrition and therefore requiring less frequent replacement), and other favorable qualities lowering costs associated with essential catalytic unit operations present in CTL processes.

2. Process Efficiency Improvements

In general, enhanced process and engineering approaches should allow improvements in efficiency, throughput, and/or reductions in greenhouse gas emissions of CTL processes by reducing the energy required to power the process. These will likely include the concept of process intensification, in which compact and efficient reactors use less space to enable more reaction throughput; improved heat exchange and heat management boosting thermal efficiency of processes and resulting in more product per amount of feedstock input; hybrid technologies that combine aspects of synthesis gas conversion or liquids processing (upgrading) technologies; and other process improvements which may be suggested by new R&D directions in the CTL technology area.

3. Multiple or blended feedstocks

Utilizing mixed coal/biomass and/or coal/natural gas feedstocks for CTL processes has the aggregate effect of lowering the life-cycle GHG of produced fuels. Technology to enable effective co-feeding and processes capitalizing on feedstock balancing, optimizing processes for lower life-cycle GHG emissions, etc., were within the scope of work called for in the solicitation.

VI. Summary

The DOE-DoD feasibility assessment of technologies for producing alternative liquid fuels from coal identified the following considerations:

- CTL processes are successfully deployed in several commercial applications and will continue to be developed internationally—especially if the price of crude oil is high.
- CTL fuels produced via F-T synthesis are already approved for incorporation into commercial and military fuels, but other pathways (e.g., pyrolysis) would require further evaluation and approval before being incorporated into commercial fuel supplies.
- Commercial CTL production processes result in approximately twice the life-cycle GHG emissions of petroleum fuel production, so substantial technology improvement is needed to enable production of CTL fuels that meet DoD's requirements for fuels procured

explicitly as alternative fuels (i.e., compliant with EISA section 526 and cost-competitive with petroleum fuels).

- In order to increase the efficiency with which coal is converted to fuels, opportunities to improve current process technologies can be found in feed systems, gasification systems, synthesis gas cleanup systems, separations systems, and conversion processes.
- Although conversion technology improvements will reduce costs and emissions, for CTL fuels to reach or surpass production cost-competitiveness and life-cycle GHG emissions parity with petroleum fuels, additional progress in at least one of the following two areas would need to be made:
    - Reduce costs of incorporating low-GHG emissions feedstocks (e.g., biomass), or
    - Enable policy acceptance and technical demonstration of CCUS pathways.
- R&D in coal gasification, carbon capture, and liquid fuels synthesis ongoing at DOE contributes towards required technology development needs.

Ultimately, ongoing work and new R&D projects will address CTL technology areas that require further development to meet cost, quality, and emissions goals demanded by the military and commercial sectors.

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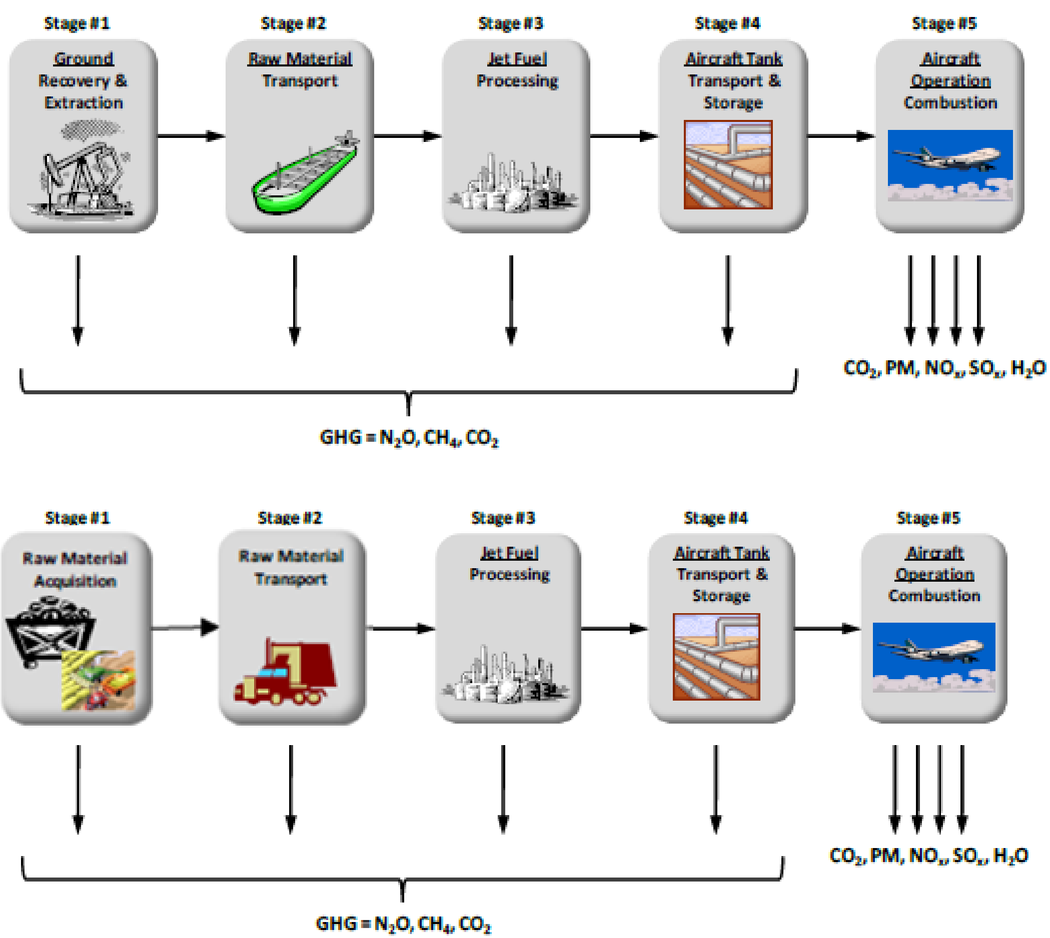
Appendix A. Life-cycle GHG Emissions—Methodology, Policy, and Economic Considerations for Coal-based Fuels

1. Methodology

Life-cycle assessment (LCA) is a framework employed to account for environmental impacts throughout the supply chain, production cycle, use cycle, and disposal of products and services. Figure 4 shows the general scheme of stages involved in evaluating the life-cycle greenhouse gas (GHG) footprint of fuel production pathways, and Figure 5 shows how the emissions of coal-based fuels compare to petroleum and other alternative fuels. Although a single point estimate is shown in Figure 5 for petroleum-based gasoline (approximately 83 g CO_2/MJ), previous studies have reported well-to-tank emissions that range from 11 to 35 g CO_2/MJ for diesel fuel produced from various types of crude oil—resulting in life-cycle emission factors up to 110 g CO_2eq/MJ [41].



a)

b)

Figure 4. Simplified system boundary for life-cycle GHG assessment of liquid jet fuels produced from a) conventional petroleum [reproduced from [42]] and b) coal/biomass [modified from [43]]

One shortcoming associated with the simplified schematic presented in Figure 4 is the lack of attention to co-products (e.g., electricity, waste heat, industrial materials) and fuel product

differentiation (e.g., F-T diesel has slightly different properties from petroleum diesel), though life-cycle analysts and fuel experts are familiar with these considerations. The manner in which GHG emissions are allocated to co-products can have significant and variable impacts on the GHG footprint assigned to fuel products [44,45]. Additionally, if CTL fuels do not exhibit precisely the same operational performance and maintenance requirements as petroleum fuels, quantifying these differences would be necessary to prevent over- or under-allocation of emissions associated with operation (combustion), engine maintenance, etc. Furthermore, emissions associated with constructing and maintaining refining facilities, storage, and distribution equipment, are ignored in most life-cycle analyses, but such embodied emissions have been shown to increase the life-cycle GHG footprint of cellulosic biofuels by several percent [31]. Given the significance of capital expenses to the total cost of F-T fuels, as presented in Figure 6, embodied emissions from constructing CTL production facilities may also be greater than the emissions embodied in petroleum refining infrastructure.

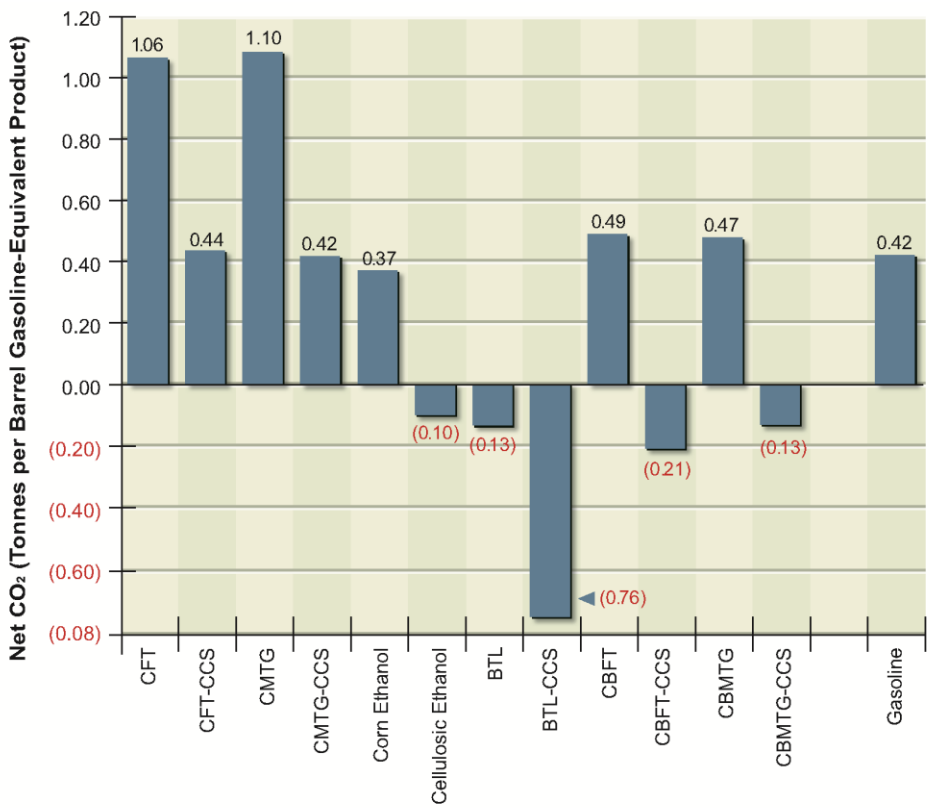


Figure 5. Estimated carbon dioxide (CO_2) emissions over the life cycle of alternative fuels, from the mining and harvesting of resources to the conversion process to the consumption of fuels [reproduced from [6]][5]

[5] Abbreviations: BTL = biomass-to-liquid fuel; CBFT = coal-and-biomass-to-liquid fuel, Fischer-Tropsch; CBMTG = coal-and-biomass-to-liquid fuel, methanol-to-gasoline; CCS = carbon capture and storage; CFT = coal-to-liquid fuel, Fischer-Tropsch; CMTG = coal-to-liquid fuel, methanol-to-gasoline.

2. Relationship between GHG Emissions Controls and Fuel Production Costs

If new coal-based fuel production facilities were to be built in the United States, CTL fuel products have been estimated to be cost-competitive with petroleum fuels when petroleum is expected to remain above a certain price point (along with other assumptions about market conditions and project lifetime). For example, several studies have estimated that CTL fuels (without biomass and without a price on CO_2 emissions) could be sold for a breakeven price of less than \$3/gallon [26,36,46,47]. In the future, potential climate policies may prevent the construction of CTL facilities that do not include CCUS, or may introduce a price on GHG emissions (e.g., through a tax or cap-and-trade system). Such policies would impact the economic viability of CTL facilities, the likelihood that such facilities would introduce CCUS, and/or the incentive for facilities to supplement coal with other feedstocks such as biomass. Figure 6 presents the estimated cost of fuels produced through a variety of these potential pathways, without considering a price on CO_2 emissions.

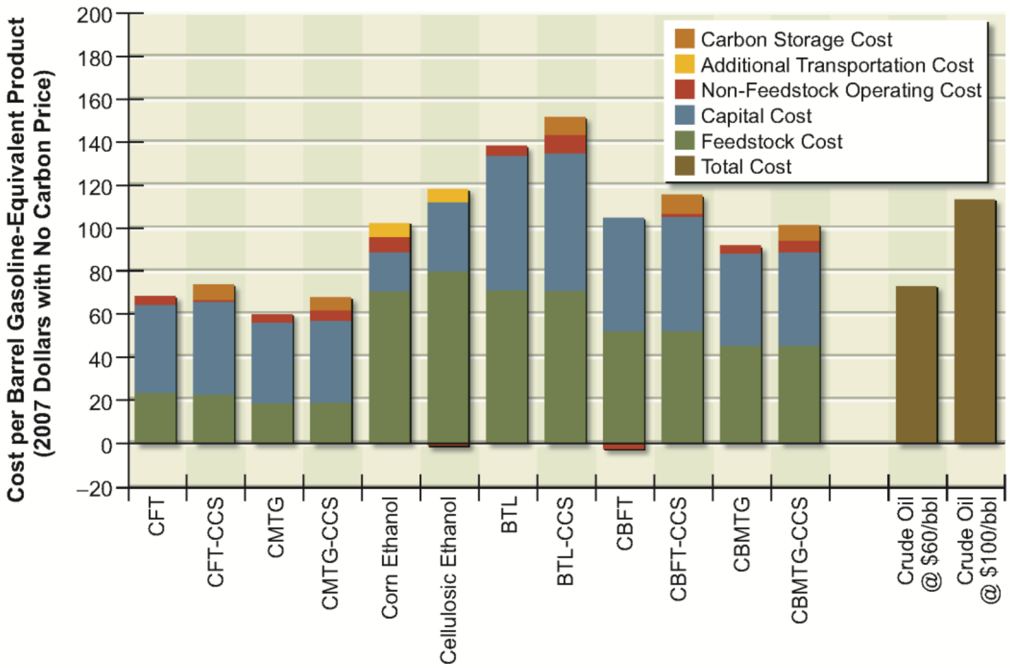


Figure 6. Costs of alternative liquid fuels produced from coal, biomass, or coal and biomass with zero carbon price [reproduced from [6]][6]

The capital cost of a 50,000 barrel-per-day (bpd) CTL facility without CCS has been estimated at \$110,000/daily barrel (\$5.5 billion in total). For comparison, a CBTL facility that utilizes 15 percent switchgrass by mass and incorporates CCS would cost approximately \$123,000/daily barrel (\$6.15 billion in total), as both features drive up capital costs [36]; Figure 7 presents an estimated breakdown of capital costs by component for this configuration. Figure 8

[6] Abbreviations: BTL = biomass-to-liquid fuel; CBFT = coal-and-biomass-to-liquid fuel, Fischer-Tropsch; CBMTG = coal-and-biomass-to-liquid fuel, methanol-to-gasoline; CCS = carbon capture and storage; CFT = coal-to-liquid fuel, Fischer-Tropsch; CMTG = coal-to-liquid fuel, methanol-to-gasoline.

demonstrates the break-even price of CTL, CBTL, and BTL fuels under various petroleum prices, various carbon prices, and fixed economic conditions.

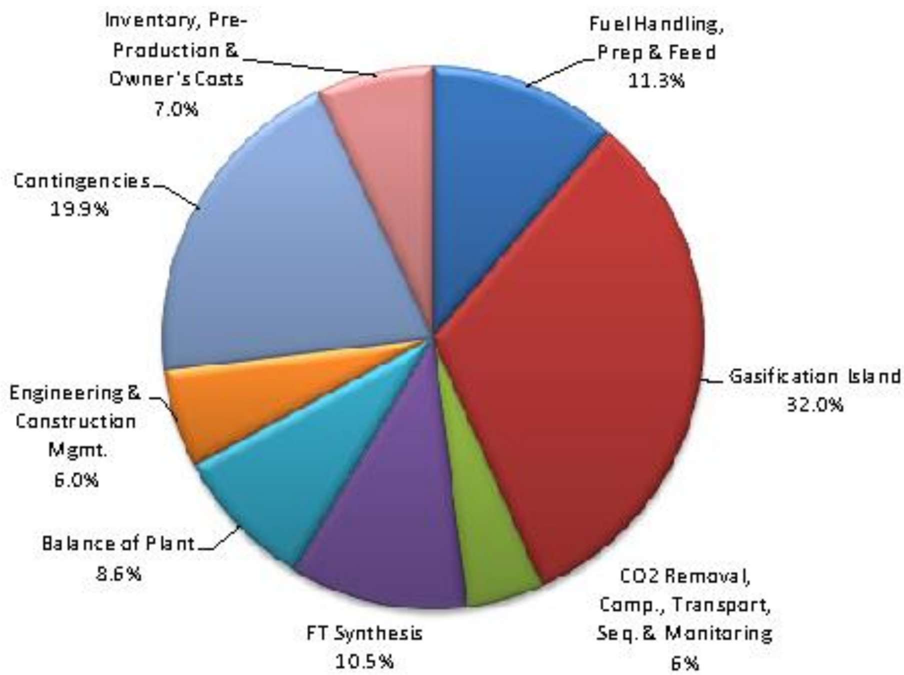


Figure 7. Distribution of total overnight capital costs for a 50,000 bpd CBTL+CCS facility designed for a biomass input of 15 percent switchgrass by weight [reproduced from [36]]

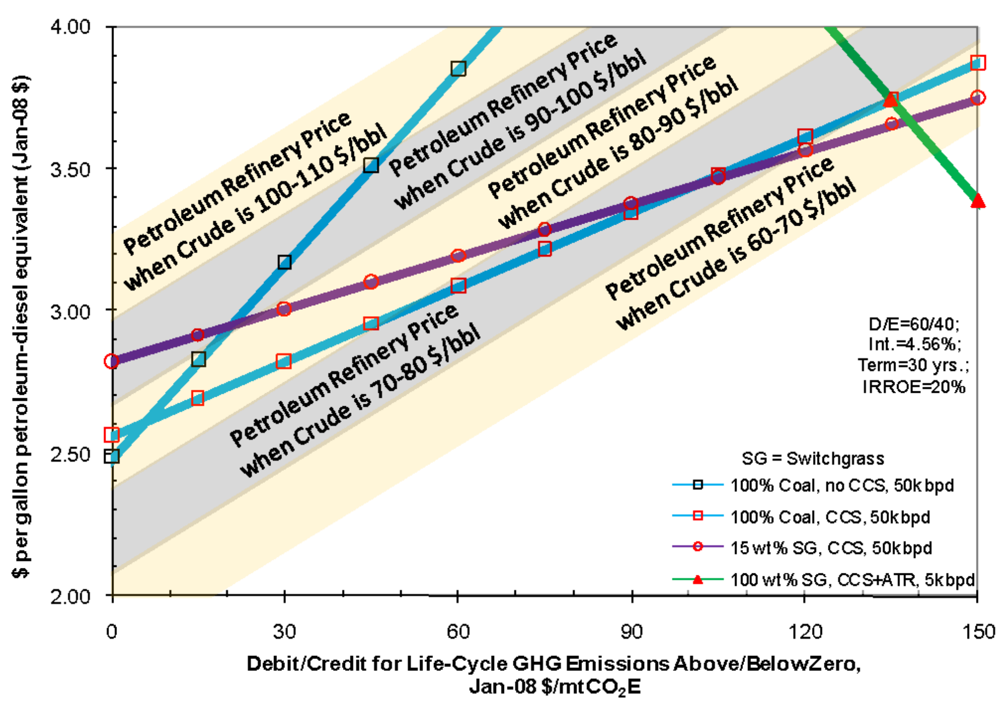


Figure 8. Conditions required for parity between the prices of F-T diesel and petroleum-derived diesel [reproduced from [36]]

Appendix B. Unit Operations of Coal-to-Liquids Processes—Improvement Possibilities

Below is a list of ongoing and future potential areas of technical research that hold promise for increasing the energy efficiency of converting coal into liquid fuels.

- Feedstock handling and feeding* (high pressure solid feeding, improved biomass/waste co-feed with coal)
- Lower temperature and pressure reactions (reduced capital cost of gasifiers and vessels and reduced operating costs)*
- Better heat recovery and heat exchangers (reduced capital costs of exchangers and increased thermal efficiency of processes)
- Better heat transfer in reactors and reaction intensification (reduced recycle rates and compact F-T)
- Microchannel hydrocracking wax to jet and distillate
- Catalyst development
    - Lower cost materials/disposable
    - Increase selectivity to more valuable products; limit chain growth to desired molecule size (e.g., >60% in jet range)
    - Copper-based
    - Carbon nanotube-based
- Water-gas shift reaction reduction or elimination through improved process cycles, integrated gas separations in reactors*
- Syngas clean-up* (sulfur, particulates, toxics)
- Oxygen production*
    - Membrane systems (ITM, OTM)
    - Developmental technology (biomimetic oxygen separation, etc.)
- Compressor systems* (shock compression, etc.)
- CO_2 and hydrogen separation technologies*
    - Sorbents
    - Solvents
    - Membranes
    - Cryogenic
- Steam cracking/reforming
- Product upgrading processes
- Innovative gasification approaches (e.g., molten salt gasification, biological conversion)
- Microwave/electromagnetic processes
- Chemical looping*
    - Used with F-T reactor, can be source of steam for hydrogen reactor
- Partial-oxidation/chemical looping (POx-CLR)

*Significant ongoing work in these areas exists in the DOE R&D program.

Appendix C. Areas of Interest under NETL-DoD Coal-to-Liquids R&D Funding Opportunity Announcement (DE-FOA-0000981)

Applications are sought under this FOA for short-term (5-15 year out) advanced coal-based technological pathways forward that would lead to the commercial production of coal-derived jet fuel with the priority objectives being that lifecycle GHG emissions are less than or equal to conventional petroleum-based jet fuel production, while also being cost-competitive with conventional petroleum-based jet fuel. (Applicants'/Recipients' cost share must be at least 20 percent of the total allowable costs.)

1. Hybrid CTL Processes for Jet Fuel Production

Under AOI 1, applications are sought for R&D of hybrid approaches, with a preference for drop-in jet fuel production. Example hybrid approaches include, but are not necessarily limited to: (1) Technologies that combine aspects of both direct and indirect coal conversion technologies; and, (2) Use of multiple or blended carbon feedstocks (e.g., coal with natural gas and/or biomass). Other innovative hybrid approaches will also be considered.

2. Process Intensification for Coal Conversion for Jet Fuel Production

Example process intensification approaches include but are not necessarily limited to: (1) Technologies that combine aspects of synthesis gas conversion or liquids processing (upgrading) technologies; (2) Use of multi-functional and selective catalysts; and, (3) Enhanced process/engineering approaches leading to improvements in efficiency, throughput, and/or reductions in greenhouse gases emissions, etc.

3. Innovative Non-Traditional Coal Conversion Processes for Jet Fuel Production

Under AOI 3, applications are sought for R&D for other novel transformational coal conversion technologies and approaches that would lead to substantial, breakthrough benefits in terms of reductions in costs and/or in lifecycle GHG emissions relative to those of petroleum-based jet fuel. The proposed novel non-traditional technologies could include non-geological CCS with the objective of achieving a GHG footprint significantly below that of the petroleum baseline.

4. Commercialization Analysis for Construction of a Site Specific CTL Facility*

The intent of AOI 4 is to provide financial assistance in conducting a site-specific feasibility study, which is the essential first step in the development of a commercial project. Applications are sought to determine the optimum plant configuration of a commercial-scale, market-competitive, and low-carbon footprint CTL fuels (including jet fuel) plant. Proposed projects will include an initial control estimate and techno-economic feasibility study which may be associated with the retrofit of an existing coal plant with first generation CTL and CCS technologies, or the construction of a Greenfield CTL plant with CCS technologies. The estimate should be consistent at a minimum with an AACE International (formerly known as the

Association for the Advancement of Cost Engineering) Class 3 estimate outlined in the AACE International Recommended Practice No. 18R-97[7].

* Supported by DOE/NETL funds

[7] Available at http://www.aacei.org/resources/rp/
Non-members of AACE must first set up a free user account in the AACE Portal in order to access recommended practices.